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The alignment between the distribution of satellites and the orientation of their central galaxy

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ABSTRACT

We use galaxy groups selected from the Sloan Digital Sky Survey to examine the alignment between the orientation of the central galaxy (defined as the brightest group member) and the distribution of satellite galaxies. By construction, we therefore only address the alignment on scales smaller than the halo virial radius. We find a highly significant alignment of satellites with the major axis of their central galaxy. This is in qualitative agreement with the recent study of Brainerd, but inconsistent with several previous studies who detected a preferential minor-axis alignment. The alignment strength in our sample is strongest between red central galaxies and red satellites. On the contrary, the satellite distribution in systems with a blue central galaxy is consistent with isotropic. We also find that the alignment strength is stronger in more massive haloes and at smaller projected radii from the central galaxy. In addition, there is a weak indication that fainter (relative to the central galaxy) satellites are more strongly aligned. We present a detailed comparison with previous studies, and discuss the implications of our findings for galaxy formation.

Key words: methods: statistical – galaxies: haloes – galaxies: structure – dark matter – large-scale structure of Universe.

1 INTRODUCTION

During the hierarchical assembly of dark matter haloes, progenitor haloes often survive accretion on to a larger system, thus giving rise to a population of subhaloes. If the baryonic material in the progenitor haloes managed to cool and form stars before being accreted, the population of subhaloes will give rise to a population of satellite galaxies. Meanwhile, gas that cools on to the centre of the parent halo gives rise to a so-called central galaxy.

Since satellite galaxies are typically distributed over the entire dark matter halo, they are ideally suited as a tracer population of the potential well in which they orbit. Consequently, they have been used extensively as dynamical tracers of the dark matter mass distribution surrounding central galaxies. In addition to providing accurate dynamical masses of the haloes (e.g. Zaritsky et al. 1993, 1997a; McKay et al. 2002; Brainerd & Specian 2003; van den Bosch et al. 2004), the radial trend of the projected velocity dispersion of satellite galaxies can also put constraints on the radial density distribution of the dark matter (Prada et al. 2003). Similar constraints can also come from the measurement of individual satellite orbits, such as that of the Large Magellanic Cloud or the Sagittarius stream in the Milky Way halo (e.g. Ibata et al. 2001; Helmi 2004; Kallivayalil et al. 2006).

In addition to these kinematics, the *spatial* distribution of satellite galaxies also holds important information. If subhaloes are a fair tracer of the dark matter mass distribution, i.e. if they are not spatially biased in any way, the radial and angular distribution of satellite galaxies directly reflects the projected distribution of the dark matter. If, on the other hand, there is a spatial bias, the satellite distribution holds important clues regarding the actual assembly history of the dark matter haloes.

Numerical simulations predict that the spatial distribution of subhaloes is biased in two distinct ways. First of all, the radial distribution of subhaloes is found to be less centrally concentrated than the dark matter, with a pronounced deficit of subhaloes near the centre

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(Ghigna et al. 1998; Colín et al. 1999; Ghigna et al. 2000; Springel et al. 2001; De Lucia et al. 2004; Diemand, Moore & Stadel 2004; Gao et al. 2004; Mao et al. 2004; Nagai & Kravtsov 2005). A similar prediction has also been obtained with detailed, semi-analytical models (Zentner et al. 2005a, but see also Taylor & Babul 2004). Somewhat surprisingly, the observed spatial distribution of satellite galaxies, especially in clusters, appears to be more centrally concentrated and not as strongly antibiased as this predicted distribution of subhaloes (Carlberg, Yee & Ellingson 1997; van der Marel et al. 2000; Lin, Mohr & Stanford 2004; Chen et al. 2005; van den Bosch et al. 2005; Yang et al. 2005c). A possible explanation, which needs to be explored in detail, is that the addition of baryons makes the subhaloes more resilient to tidal disruption.

In addition to this radial antibias, numerical simulations have also suggested an angular bias. In particular, numerous studies have shown that dark matter haloes in dissipationless simulations have anisotropic distributions of subhaloes that are aligned with their major axis (Knebe et al. 2004; Libeskind et al. 2005; Wang et al. 2005; Zentner et al. 2005b). This anisotropy mainly owes to a preferred direction of satellite accretion along large-scale filaments (Tormen 1997; Vitvitska et al. 2002; Aubert, Pichon & Colombi 2004; Knebe et al. 2004; Wang et al. 2005; Zentner et al. 2005b). Since the orientation of the halo itself is largely governed by the directionality of its mass accretion (e.g. van Haarlem & van de Weygaert1993; Tormen 1997), this naturally explains the alignment of the subhaloes with the major axis of the parent halo. It is important to distinguish here between simple angular anisotropy of the subhalo distribution, and a true angular bias. Even in the absence of any spatial bias, any non-sphericity of dark matter haloes will result in a projected, angular anisotropy of the subhalo distribution, unless the halo is seen along its symmetry axis. Both Wang et al. (2005) and Agustsson & Brainerd (2005a) have shown that the non-sphericity of the halo is the main cause of the theoretical angular anisotropy, but that there is a weak indication for some additional angular bias with a preferred alignment along the major axis of the halo.

If the orientations of central galaxies are somehow aligned with their dark matter haloes, this anisotropy should result in an observable correlation between the distribution of satellite galaxies and the orientation of their central galaxy. Numerical simulations suggest that the angular momenta of dark matter haloes are typically aligned with their minor axes (e.g. Dubinski 1992; Warren et al. 1992; Porciani, Dekel & Hoffman 2002a; Bailin & Steinmetz 2005; Faltenbacher et al. 2005; Wang et al. 2005). If the angular momentum vector of the baryonic material is well aligned with that of the dark matter, one would thus naively expect the spin axes of disc galaxies to be aligned with the minor axes of their host haloes, and the satellite galaxies to be preferentially oriented along the major axis of the disc. However, detailed hydrodynamical simulations reveal a more complicated picture. First of all, even in the absence of cooling the spin axes of the baryons and the dark matter are only poorly aligned, with a median misalignment angle of about $\sim 20^\circ$ to $\sim 30^\circ$ (van den Bosch et al. 2002; Chen, Jing & Yoshikawa 2003; Sharma & Steinmetz 2005). Furthermore, in simulations of disc galaxy formation that include cooling, the orientation of the disc spin axis is found to be virtually uncorrelated with the original (i.e. in the absence of baryons) minor axis of the halo (Bailin et al. 2005). The formation of the disc modifies the shape and orientation of the inner halo, but leaves the outer halo largely intact (Kazantzidis et al. 2004; Bailin et al. 2005). Consequently, the disc spin axis is well aligned with the halo minor axis in the inner halo ($r \lesssim 0.1 r_{\rm vir}$), but is basically uncorrelated with the minor axis at larger halocentric radii. If correct, this would predict basically no alignment between the orientation of the central disc galaxy and the distribution of its satellites (most of which lie at relatively large halocentric radii).

The observational search for a possible alignment between central galaxies and their satellites has a long and confusing history. Holmberg (1969) studied the distribution of satellite galaxies around isolated disc galaxies, and found them to lie preferentially along the minor axis of disc galaxies. Holmberg's study was restricted to projected satellite-central distances of $r_{\rm p} \lesssim 50$ kpc. Subsequent studies, however, were unable to confirm this so-called 'Holmberg effect' (Hawley & Peebles 1975; Sharp, Lin & White 1979; MacGillivray et al. 1982). Zaritsky et al. (1997b, hereafter ZSFW97) were also unable to detect any significant alignment for $r_{\rm p} \lesssim 200$ kpc, but they *did* detect a preferred minor-axis alignment for separations in the range 300 kpc $\lesssim r_{\rm p} \lesssim$ 500 kpc. Note that this implies an alignment on scales larger than the typical virial radii of the haloes hosting these isolated disc galaxies. This large-scale ($r_{\rm p} < 500$ kpc) alignment has recently been confirmed by Sales & Lambas (2004, hereafter SL04), using data from the two-degree Field Galaxy Redshift Survey (2dFGRS), but only for host–satellite pairs with a line-of-sight velocity difference of $|\Delta v| < 160\,{\rm km\,s^{-1}}$. Our own Milky Way (MW) also reveals a Holmberg effect, in that the 11 innermost MW satellites (with MW distances $\lesssim$250 kpc) show a pronounced planar distribution oriented close to perpendicular to the MW disc (Lynden-Bell 1982; Majewski 1994; Kroupa, Theis & Boily 2005). Completely opposite to all theses results, Brainerd (2005, hereafter B05) and Agustsson & Brainerd (2005b) recently found that, in the Sloan Digital Sky Survey (SDSS), the distribution of satellite galaxies with $r_{\rm p} \lesssim 100$ kpc is strongly aligned with the *major* axis of the disc host galaxy. As a summary, we list in Table 1. The main attempts in searching for the alignment signal between the central galaxies and their satellites.

Clearly, this lack of agreement calls for a more in-depth study. In this paper, we investigate the alignment between satellite galaxies and their host galaxies using data from the SDSS. Our approach, however, differs substantially from all previous studies. First of all, previous studies only focused on relatively isolated disc galaxies, which has the disadvantages that it drastically reduces the sample size, and that one only selects haloes in relatively low-density environments. In addition, satellite galaxies were always selected in a fixed metric aperture centred on the host galaxy. For low-luminosity hosts, which reside in low-mass haloes, this metric is often much larger than the expected virial radius of the host halo. In this paper we study the host–satellite alignment using a large sample of galaxy groups. No isolation criteria are applied, which allows us to (i) achieve much better statistics and (ii) to investigate how the alignment strength depends on various properties of the host halo, the host galaxy and the satellite galaxies. In addition, we only focus on satellites that are located within the virial radius of the host halo with projected satellite-central distances $r_{\rm p} < r_{\rm vir}$ and satellite-central line-of-sight velocity differences $|\Delta v| < v_{\rm vir}$, where $r_{\rm vir}$ and $v_{\rm vir}$ are the virial radius and virial velocity dispersion of the host dark matter halo, respectively. In other words, we select satellites using a variable aperture size that is motivated by the mass of the host halo (i.e. the galaxy group). This has the important advantage that we can clearly separate small-scale alignment ($r < r_{\rm vir}$) from large-scale alignment ($r > r_{\rm vir}$). Depending on how the shapes and angular momenta of dark matter haloes are oriented with respect to their surrounding large-scale structure, the alignment on these two different scales may well be very different (see e.g. Barnes & Efstathiou 1987; Porciani et al. 2002a,b; Navarro, Abadi & Steinmetz 2004; Bailin & Steinmetz 2005; Trujillo, Carretero & Patiri 2006).

Table 1. The observational search for possible alignment between central galaxies and their satellites.

Attempt (1)	N systems (2)	Central galaxy type (3)	r_p (kpc) (4)	$\lvert\Delta v\rvert$(km s^{-1}) (5)	L_s/L_c (6)	Alignment (7)	LG included (8)
Holmberg (1969)	218	Nearby spirals	$\lesssim$50	–	–	Minor axis	YES
Zaritsky (1997b)	115	Nearby spirals	$\lesssim$200	$\lesssim$500	–	NO	–
			[300 500]	$\lesssim$500	–	Minor axis	–
SL04	1276	2dFGRS BIG[a]	$\lesssim$500	$\lesssim$160	$\lesssim$0.16	Minor axis	–
Kroupa et al. (2005)	11	Milky Way	$\lesssim$250	–	–	Minor axis	YES
B05	3292	SDSS-DR3 BIG	$\lesssim$700	$\lesssim$1000	$\lesssim$0.16	Major axis	–
	1575		$\lesssim$500	$\lesssim$1000	$\lesssim$0.25	Major axis	–
	935		$\lesssim$500	$\lesssim$1000	$\lesssim$0.125	Major axis	–
AB[b] (2005b)	4327	SDSS-DR4 BIG	$\lesssim$700	$\lesssim$500	$\lesssim$0.25	Major axis	–
This work (2006)	24 728	SDSS-DR2 GCG[c]	$\lesssim r_{\rm vir}$	$\lesssim v_{\rm vir}$	–	Major axis	–

Column (1) indicates the attempt ID. Columns (2) (number of central-satellite systems), (3) (the type of central galaxy), (4) (the projected centric-distance of the satellite galaxy), (5) (the line-of-sight velocity difference of the satellite-central system) and (6) (the luminosity fraction of the satellite-central system) indicate the selection criteria. Column (7) lists the alignment signal obtained from this observation. Column (8) lists the status of the Local Group. [a]BIG means bright isolated galaxies, [b]AB: Agustsson & Brainerd (2005b) and [c]GCG means group central galaxy.

This paper is organized as follows. In Section 2 we present the data and our methodology. Section 3 presents a careful analysis of the alignment between the orientation of central galaxies and the distribution of their satellite galaxies. In particular, we show how the alignment strength depends on the luminosity and colour of the galaxies, and on the mass of the dark matter haloes. In Section 4, we present a detailed comparison with previous studies. Finally, in Section 5 we summarize our results, and discuss their implications.

2 DATA AND ANALYSIS

2.1 Galaxy groups

In order to address the possible alignment between satellite galaxies and the central galaxy of their dark matter parent halo we use the SDSS galaxy group catalogue of Weinmann et al. (2006).[1] This catalogue was constructed from the New York University Value-Added Galaxy Catalogue (NYU-VAGC; Blanton et al. 2005)[2] using the halo-based group finder developed by Yang et al. (2005a, hereafter YMBJ). The NYU-VAGC is based on the SDSS Data Release 2 (DR2) (Abazajian et al. 2004), but with an independent set of significantly improved reductions. We only consider the galaxies with redshifts in the range $0.01 \leqslant z \leqslant 0.2$ and with a redshift completeness $c > 0.7$,[3] resulting in a sample of 184 425 galaxies with a sky coverage of $\sim$1950 deg^2.

In brief, the YMBJ group finder works as follows. First potential group centres are identified using a friends-of-friends (FOF) algorithm or an isolation criterion. Next, the total group luminosity is estimated which is converted into an estimate for the group mass using an assumed mass-to-light ratio. From this mass estimate, the radius and velocity dispersion of the corresponding dark matter halo are estimated using the virial equations, which in turn are used to select group members in redshift space. This method is iterated until group memberships converge. Detailed tests with mock galaxy redshift surveys have shown that this group finder recovers groups with an average completeness of $\sim$90 per cent and with an interloper fraction that is smaller than $\sim$20 per cent. The resulting group catalogue is insensitive to the initial assumption regarding the mass-to-light ratios, and the group finder is more successful than the conventional FOF method in associating galaxies according to their common dark matter haloes (see YMBJ for details).

Following Yang et al. (2005b), we use the group luminosity to assign masses to our groups. The motivation behind this is that one naturally expects the group luminosity to be strongly correlated with halo mass (albeit with a certain amount of scatter). For each group we determine the number density of all groups brighter than the group in consideration, using a common, empirically calibrated definition of group luminosity. From the halo mass function corresponding to a Lambda cold dark matter (ΛCDM) concordance cosmology with $\Omega_{\rm m} = 0.3, \Omega_\Lambda = 0.7, h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}}) = 0.7$ and $\sigma_8 = 0.9$ we then find the mass for which the more massive haloes have the same number density. Although this has the downside that it depends on cosmology, as shown in Weinmann et al. (2006), this method yields masses that are more accurate than those based on the more traditional line-of-sight velocity dispersion of the group members (see Weinmann et al. 2006). In addition, it is straightforward to convert the masses derived here to any other cosmology (see Yang et al. 2005b).

Applying our group finder to the sample of 184 425 galaxies in the NYU-VAGC described above yields a group catalogue of 53 229 systems with an estimated mass. These groups contain a total of 92 315 galaxies. The majority of the groups (37 216 systems) contain only a single member, while there are 9220 binary systems, 3073 triplet systems, and 3720 systems with four members or more.[4] In what follows, we use this group catalogue to examine the alignment between the orientation of the central galaxy, defined as the brightest group member, and the distribution of satellite galaxies. Note that we have a total of 39 086 unique central-satellite pairs, which is an order of magnitude larger than in any previous study.

2.2 Methodology

In order to quantify the distribution of satellite galaxies in groups relative to the orientations of their central galaxies we follow B05

[1]In this paper, we refer the brightest member in each group as the central galaxy, while all other members as satellite galaxies.

[2]http://wassup.physics.nyu.edu/vagc/#download

[3]Because of the survey selection effects (e.g. fibre collisions, etc.) not all galaxies in the photometric catalogue are spectroscopically observed and thus their spectroscopic redshifts are measured.

[4]The group catalogue is publicly available at http://www.astro.umass.edu/~xhyang/Group.html.

and compute the distribution function, $P(\theta)$, where θ is the angle on the sky between the major axis of the 25-mag arcsec^{-2} isophote in the r band of the central group galaxy and the direction of a satellite relative to the central galaxy. We restrict θ to the range [0°, 90°], where $\theta = 0°$ (90°) implies that the satellite lies along the major (minor) axis of the central galaxy. The orientation of the central galaxy is based on the isophotal position angle in the r band, as given in the SDSS-DR2 (Abazajian et al. 2004).

As mentioned above, the analysis of B05 focused on relatively isolated systems with late-type central galaxies. Our analysis is different in that we consider galaxy groups of various properties. In practice, we start with a group sample and count the total number of central-satellite pairs, $N(\theta)$, for a number of bins in θ. Next, we construct 100 random samples in which we randomize the orientation of all central galaxies, and we compute $\langle N_{\rm R}(\theta)\rangle$, the average number of central-satellite pairs as function of θ. Note that this ensures that the random samples have exactly the same selection effects as the real sample, so that any significant difference between $N(\theta)$ and $N_{\rm R}(\theta)$ reflects a genuine alignment between the orientation of the central galaxies and the distribution of satellite galaxies.

To quantify the strength of any possible alignment we define the normalized pair count

$$f_{\rm pairs}(\theta) = \frac{N(\theta)}{\langle N_{\rm R}(\theta)\rangle}. \quad (1)$$

Note that $f_{\rm pairs}(\theta) = 1$ in the absence of any alignment. We use $\sigma_{\rm R}(\theta)/\langle N_{\rm R}(\theta)\rangle$, where $\sigma_{\rm R}(\theta)$ is the s.d. of $N_{\rm R}(\theta)$ obtained from the 100 random samples, to assess the significance of the deviation of $f_{\rm pairs}(\theta)$ from unity. In addition to this normalized pair count, we also compute the average angle $\langle\theta\rangle$. In the absence of any alignment $\langle\theta\rangle = 45°$, however, $\langle\theta\rangle = 45°$ does not mean an isotropic distribution. The significance of any alignment can be expressed in terms of $\langle\theta\rangle$ and σ_θ, the variance in $\langle\theta\rangle_{\rm R}$ as obtained from the 100 random samples.

Finally, since the accuracy with which θ can be measured scales with the projected ellipticity of the central galaxy, we only consider groups for which the ellipticity of the central galaxy, $e \geqslant 0.2$. Here e is defined as one minus the ratio between the minor and major axes of the 25-mag arcsec^{-2} isophote in the r band of the image of the central galaxy. This ellipticity constraints bring the total number of unique central-galaxy pairs to 24 728.

3 RESULTS

Fig. 1 shows $f_{\rm pairs}(\theta)$ for all groups in our SDSS group catalogue with inferred halo masses of $M \geqslant 10^{12}\,h^{-1}\,{\rm M}_\odot$ and with central galaxies that have $e > 0.2$. Note the pronounced enhancement of pairs with small θ, implying that satellite galaxies are preferentially distributed along the major axes of their central galaxies. This is also evident from the fact that $\langle\theta\rangle = 42.^\circ2 \pm 0.^\circ2$, which deviates from the case of no alignment (i.e. $\langle\theta\rangle = 45.^\circ0$) by 14σ!

Since the accuracy of the orientation angle of a central galaxy is smaller for central galaxies that appear rounder, the strength of the alignment may be diluted due to central galaxies with a small ellipticity, e. In order to address the impact of e on the strength of the alignment signal, the upper panels of Fig. 2 show $f_{\rm pairs}(\theta)$ for groups with central galaxies with different ellipticities, as indicated. Note that the alignment strength is weakest for the sample with the highest ellipticities ($0.6 \leqslant e < 0.8$). This is surprising since one would expect the orientation angle of these central galaxies to be the most accurate. However, as we will see in Section 3.1, the strength of the alignment is significantly weaker for systems with blue, late-type central galaxies than for systems with red, early-type central

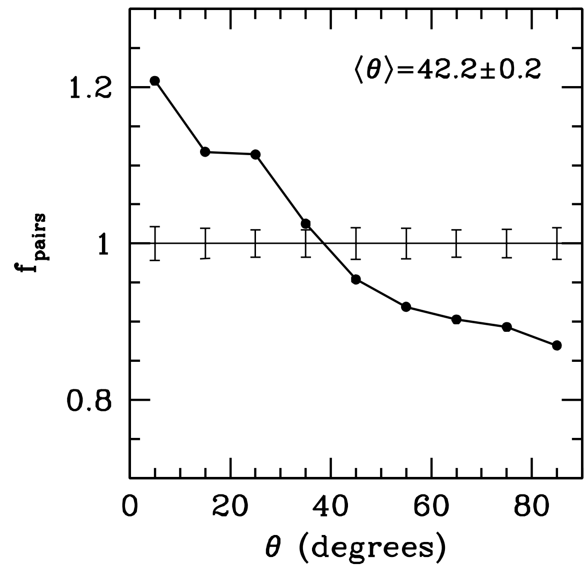

Figure 1. The normalized probability distribution of the angle θ between the orientation of the major axis of the central group galaxy and the direction of each satellite as measured from the central galaxy. These results have been obtained from the SDSS group catalogue discussed in the text, where we have excluded those groups for which the projected ellipticity of the central galaxy is less than 0.2. This leaves a grand total of 24 728 unique central-satellite pairs. The normalization and error bars are computed from 100 random samples in which we have randomized the orientation of all central galaxies (see text for details). Note that $f_{\rm pairs} > 1$ for $\theta < 35°$ indicating that the satellite galaxies are preferentially distributed along the major axis of their central galaxy. This is also evident from the average value of θ, and its error, which are indicated in the upper right-hand corner. Note that an isotropic satellite distribution corresponds to $\langle\theta\rangle = 45°$.

galaxies. The dependence on e found here is simply due to the fact that central galaxies with $e \geqslant 0.6$ are dominated by blue, late-type, disc galaxies. In what follows, we always use all groups with central galaxies with $e \geqslant 0.2$.

3.1 Dependence on galaxy properties

Since our group catalogue contains a large number (~39 000) of central-satellite pairs, it allows us to study how the alignment depends on various properties of the central and satellite galaxies. We start by examining the dependence on the luminosities of the satellite galaxies. The lower panels of Fig. 2 show $f_{\rm pairs}(\theta)$ for a number subsamples of satellite galaxies that are selected based on their luminosities, $L_{\rm s}$, relative to the luminosities of their central galaxies, $L_{\rm c}$. There is a weak trend that fainter satellite galaxies are more strongly aligned with the orientation of their central galaxy than brighter satellite galaxies.

Next, we consider the dependence on the colour of the satellite galaxies. We separate galaxies into two subsamples according to their $^{0.1}(g-r)$ colours, which corresponds to the $(g-r)$ colour k-corrected to redshift $z = 0.1$. We call galaxies with $^{0.1}(g-r) < 0.83$ 'blue' and galaxies with $^{0.1}(g-r) \geqslant 0.83$ 'red'. This value of 0.83 roughly corresponds to the bimodality scale in the colour–magnitude relation (see Weinmann et al. 2006).

The upper panels of Fig. 3 show $f_{\rm pairs}(\theta)$ for blue and red *satellite* galaxies, while the lower panels show $f_{\rm pairs}(\theta)$ for groups with blue and red *central* galaxies. Note that there is a remarkably strong dependence on the colour of both the central galaxies and the satellite

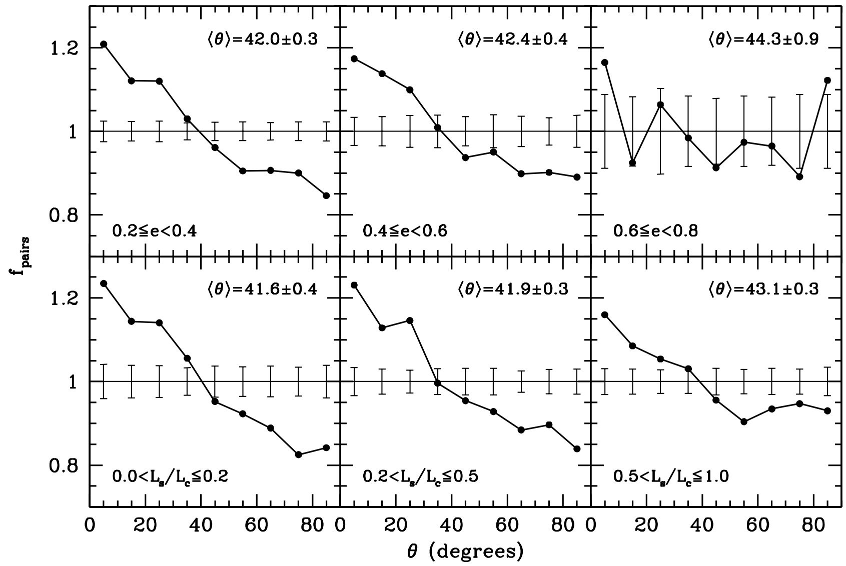

Figure 2. Same as Fig. 1 but for different subsamples of central and satellite galaxies. In the upper panels, we show $f_{\rm pairs}(\theta)$ for groups with a different ellipticity, e, of the central galaxy, as indicated. Note that groups with a strongly elongated central galaxy ($0.6 \leqslant e < 0.8$) are consistent with a perfectly isotropic distribution of satellites. As we argue in the text, and show in Fig. 3, this owes to the fact that strongly elongated systems are mainly blue, late type disc galaxies, which show no significant alignment. The lower panels show how $f_{\rm pairs}(\theta)$ depends on the luminosities of the satellite galaxies, $L_{\rm s}$, expressed in units of the luminosity of their central galaxy, $L_{\rm c}$. There is a clear indication that fainter satellites are more strongly aligned.

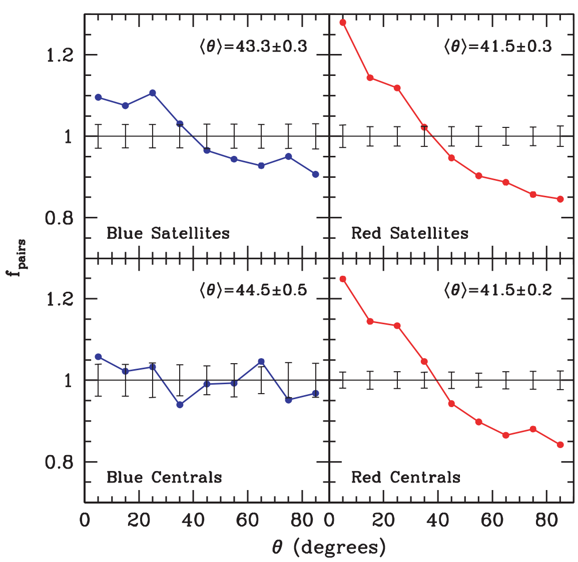

Figure 3. Same as Fig. 1, but for different subsamples of hosts and satellites, selected according to their $^{0.1}(g-r)$ colour. See text for discussion.

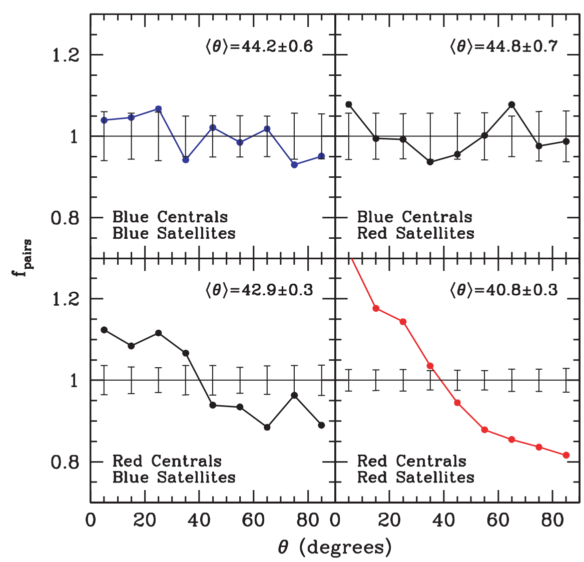

Figure 4. Same as Fig. 3, except that here we split the sample according to the colours of *both* the central and the satellite galaxies, as indicated.

galaxies. In particular, satellite galaxies in groups with a blue, central galaxy are consistent with a perfectly isotropic distribution; there is no sign of any significant alignment ($\langle\theta\rangle = 44^{\circ}\!.5 \pm 0^{\circ}\!.5$). On the contrary, groups with a red central galaxy show a very pronounced, major-axis alignment with $\langle\theta\rangle = 41^{\circ}\!.5 \pm 0^{\circ}\!.2$. In addition, red satellites show a significantly stronger major-axis alignment than blue satellites.

As shown in Weinmann et al. (2006), haloes with a central red galaxy have a significantly larger fraction of red satellites than a halo of the same mass, but with a blue central galaxy. This so-called 'galactic conformity' implies that the upper and lower panels are not independent. In Fig. 4, we therefore examine how $f_{\rm pairs}(\theta)$ depends on the colours of *both* the central galaxy and the satellites. As can be seen, systems with a blue central galaxy show no significant alignment, neither with their blue satellites nor with their red satellites. Systems with a red central galaxy, however, show a very pronounced alignment, which is significantly stronger for red satellites than it is for blue satellites. Since redder colours typically indicate older stellar populations, these results suggest that a significant alignment between the orientation of central galaxies and the distribution of their satellite galaxies only exists in haloes with a relatively old stellar population. Clearly, such a correlation between the alignment strength and the age of the stellar population must

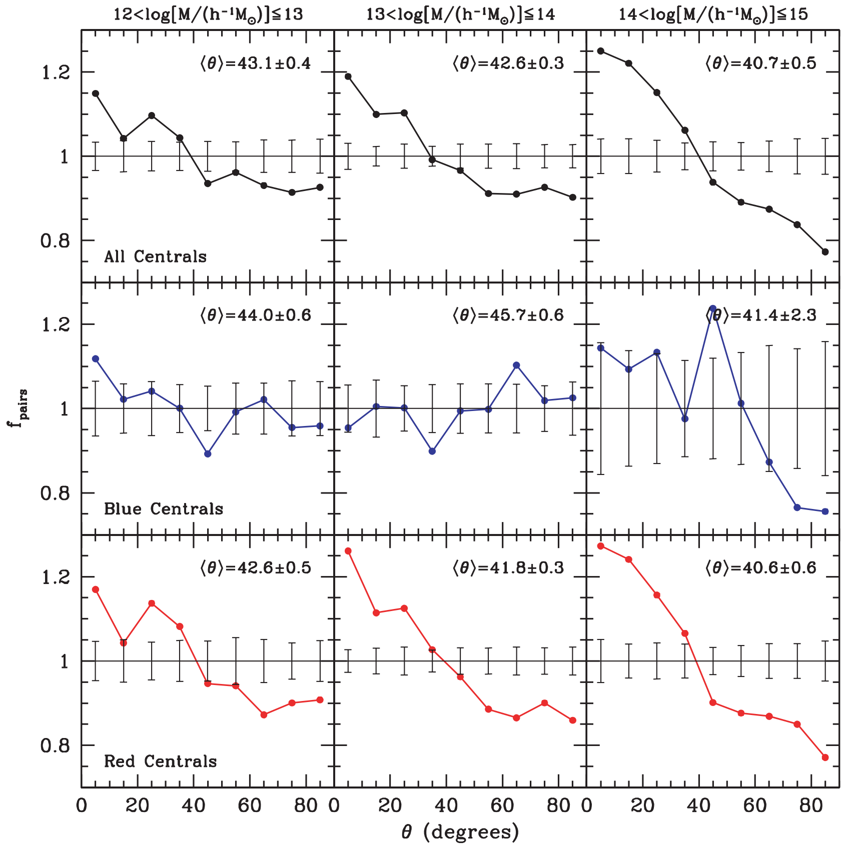

Figure 5. Same as Fig. 1, but for satellite-central galaxy pairs in haloes of different mass bins as indicated at the top of the panels. In the upper panels we show the results using all groups with $e \geqslant 0.2$, independent of the colour of the central galaxies. Note that there is a weak trend of increasing alignment strength with increasing halo mass. Panels in the middle and lower rows correspond to haloes in the same mass ranges but with only blue and red central galaxies, respectively. Note that haloes with blue, central galaxies show no significant alignment of their satellite distribution with the orientation of the central galaxy, independent of halo mass. Haloes with a red, central galaxy on the other hand, always reveal a major-axis alignment, with a strength that increases with halo mass.

hold some interesting clues regarding galaxy formation. We return to this in Section 5.

3.2 Halo mass dependence

It is interesting to examine whether the alignment strength also depends on halo mass. Since our group catalogue covers a large range in halo masses, we can address this question in some detail. The upper panels in Fig. 5 show the results for groups in three mass bins, as indicated. There is a clear mass dependence, in the sense that the alignment is stronger for more massive groups.

Since more massive haloes contain a larger fraction of red galaxies (e.g. Weinmann et al. 2006), and given that red galaxies show a much more pronounced alignment than blue galaxies, this mass dependence may simply reflect the colour dependence shown in the previous section. To test this, the panels in the middle and lower row of Fig. 5 show $f_{\rm pairs}(\theta)$ for groups in the same three mass bins, but considering groups with blue or red central galaxies separately. This shows that haloes with blue central galaxies show no significant alignment, independent of their mass. Haloes with a red central galaxy, however, do show a significant alignment, with a strength that increases with increasing halo mass. Thus, there is a genuine mass dependence, but only for haloes with red central galaxies.

3.3 Radial dependence

Finally, we examine whether the alignment depends on the group-centric distance of satellite galaxies. For each central-satellite pair we compute the projected separation, r, in units of the virial radius, $r_{\rm vir}$, of the corresponding halo. Fig. 6 plots $\langle\theta\rangle$ as function of $r/r_{\rm vir}$. An isotropic satellite distribution will have $\langle\theta\rangle = 45°$, indicated by the horizontal line, while values smaller (larger) than 45° indicate a preferred alignment with the major (minor) axis of the central galaxy. As before, the error bars are obtained from the 100 randomizations of the orientations of the major axes of the central galaxies. The upper, left-hand panel shows the results for all groups with central galaxies with $e \geqslant 0.2$. There is a clear radial trend, in that satellites at smaller, projected distances from their central galaxy are more strongly aligned with its major axis. If we split the sample according to the satellite luminosity, $L_{\rm s}$, relative to that of the central galaxy, $L_{\rm c}$, there is a pronounced difference: fainter satellites do not show a significant radial dependence, while satellites with $L_{\rm s} > 0.3L_{\rm c}$ show a very strong radial trend.

The lower panels of Fig. 6 show $\langle\theta\rangle$ as function of $r/r_{\rm vir}$ for three different bins in halo mass, as indicated. Haloes with $M \lesssim 10^{14}\,h^{-1}\,{\rm M}_\odot$ reveal a significant trend of decreasing $\langle\theta\rangle$ (i.e. a stronger major-axis alignment) with decreasing radius. In more massive haloes, however, there is no significant radial trend. Instead, in these haloes the major-axis alignment is extremely strong at all projected radii.

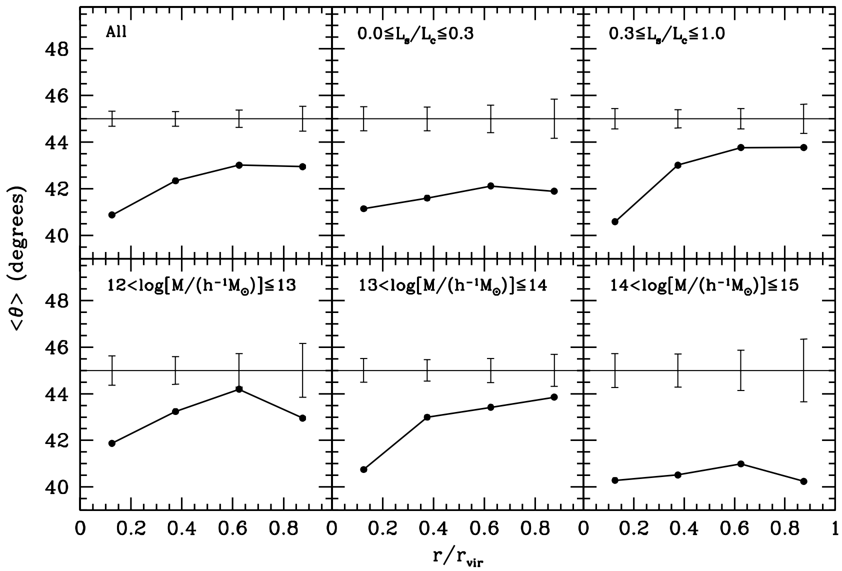

Figure 6. The average angle θ as function of the projected radius between the satellite galaxy and the central group galaxy, r, expressed in units of the virial radius of the group, $r_{\rm vir}$. The upper left-hand panel shows the result for all groups in which the central galaxy has an ellipticity $e \geqslant 0.2$. The upper panels in the middle and to the right-hand side correspond to central-satellite pairs for $L_{\rm s}/L_{\rm c}$ falls in the range indicated. The lower panels show the results for three subsamples selected according to the mass of the groups, again as indicated. The thin, horizontal line indicates $\langle\theta\rangle = 45^\circ$, which corresponds to an isotropic distribution. The error bars are computed from 100 random samples in which we randomized the orientation of all central galaxies. Overall, the major-axis alignment strength is stronger at smaller projected radii.

Fig. 7 shows how $\langle\theta\rangle(r/r_{\rm vir})$ depends on the colours of the satellites and their central galaxies. Systems with a blue central galaxy only show a weak ($\sim 3\sigma$) major-axis alignment with satellites (both red and blue) at $r \leqslant 0.2 r_{\rm vir}$. The distribution of satellites at larger projected radii is perfectly consistent with isotropic. Systems with a red, central galaxy reveal a weak, but significant, radial trend of decreasing alignment strength with increasing radius. This is most pronounced for the red satellites, while the blue satellites are consistent (within the errors) with a constant alignment strength at all projected radii.

4 COMPARISON WITH PREVIOUS STUDIES

As shown above, we detect a significant alignment of satellite galaxies with the major axis of their central host galaxy. This is in qualitative agreement with the recent studies of B05 and Agustsson & Brainerd (2005b), but in strong disagreement with Holmberg (1969), ZSFW97 and SL04.

First of all, given that many studies have been unable to reproduce the results of Holmberg (1969), and given that he used a sample consisting of only 58 hosts and 218 satellites, we argue that Holmberg's results are probably an unfortunate outcome of the small sample size. Secondly, our results are not necessarily inconsistent with those of ZSFW97, who only detected a significant minor-axis alignment at relatively large projected radii ($300\,{\rm kpc} \leqslant r \leqslant 500\,{\rm kpc}$). This is larger than the typical virial radius, $r_{\rm vir}$, expected for the isolated disc galaxies used in their study. Since we have only focused on the alignment at scales $r \leqslant r_{\rm vir}$, our results and theirs are not mutually exclusive. For $r \leqslant 200\,{\rm kpc}$ ZSFW97 did not find any indication for a significant satellite alignment. Since they only focused on isolated disc galaxies, this is in agreement with the isotropic distribution of satellites in systems with a blue central galaxy presented here. Note that ZSFW97 only had a sample consisting of 115 satellites (around 69 host galaxies).

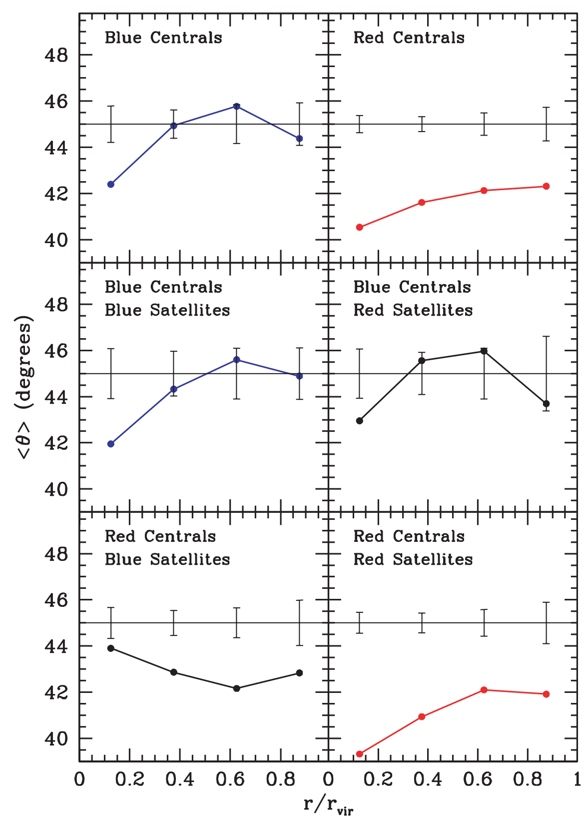

Figure 7. Same as Fig. 6 except that we show the results for different subsamples selected according to the $^{0.1}(g-r)$ colours of the central and satellite galaxies, as indicated. See text for a detailed discussion.

The results of SL04, based on the 2dFGRS, are more difficult to explain in light of our findings. In particular, SL04 also investigated how their alignment strength correlates with the properties of the central galaxies. In agreement with our results, they find that the satellite distributions around blue centrals are consistent with being isotropic, while satellites around red centrals show a strong alignment effect. However, contrary to the major-axis alignment found here, SL04 detected a *minor*-axis alignment. The fact that the same trends are detected, but in the opposite direction, is suggestive of an error in the computation of θ, and we have performed a number of tests to investigate this possibility. Unfortunately, the major-axis position angles of the 2dFGRS galaxies are defined as 'measured in degrees clockwise from east to west'.[5] This description is ambiguous as it is unclear whether an angle of 45° corresponds to north-east (as would be the case if the astronomical convention is used) or to south-east. To test this, we cross-correlate the 2dFGRS with our SDSS sample, and compare the orientation angles provided by both catalogues. This comparison indicates that the 2dFGRS orientation angles are measured from east through south. As it turns out, SL04 interpreted the orientation angles as running from east through north (Laura Sales & Diego Lambas private communication). Consequently, what they call a minor-axis alignment is in fact a major-axis alignment. In retrospect, the SL04 results are thus in qualitative agreement with B05 and with the results presented here. This has been confirmed by tests performed by the authors (Laura Sales & Diego Lambas private communication).

Finally, it is worth pointing out that our qualitative agreement with the study of B05, who also used SDSS data, is not entirely trivial. While B05 focused on relatively isolated central galaxies, we consider all galaxy systems, from poor groups to rich clusters, selected with our group finder. Furthermore, B05 only select systems in which all satellites are significantly fainter than the central galaxy (similar to ZSFW97 and SL04). In fact, the selection criteria are so restrictive, that although B05 starts out with a larger SDSS sample than used here (SDSS-DR3 versus SDSS-DR2), she ends up with less than 3300 satellites, almost an order of magnitude fewer than in our case. Given these dramatic differences, it is therefore not obvious that the results have to be compatible. We have verified, however, that if we select, from our group catalogue, those groups that obey the selection criteria of B05, we obtain results that are of slightly stronger alignment signal than those of B05. This discrepancy may partly due to the fact that the colour distribution of the remaining central galaxies are very similar to the original ones, unlike those in B05 which are mostly spiral galaxies and, in our investigations, have smaller alignment signal.

To summarize, B05 and SL04 both have obtained results that are in qualitative agreement with the results presented here: satellites around red hosts are aligned with the major axis of the host, while satellites around blue hosts have an angular distribution that is consistent with isotropic. As we have argued, these results are not necessarily inconsistent with those of ZSFW97. The only study that is in clear disagreement with our results is that of Holmberg (1969). However, given his relatively small sample size, this discrepancy is not very significant. Nevertheless, one important exception to the general picture obtained here exists, namely our own MW. As discussed in Section 1, the MW satellites reveal a pronounced planar distribution that is oriented close to perpendicular to the disc. However, as we argue below, this is not necessarily inconsistent with our results.

[5] http://www.mso.anu.edu.au/2dFGRS/

5 DISCUSSION AND CONCLUSIONS

Using galaxy groups selected from the SDSS, we have examined the alignment between the orientation of the central galaxy (defined as the brightest group member) and the distribution of its satellites. Overall, we find an excess of satellites along the major axis, and a deficiency along the minor axis, compared to an isotropic distribution. The alignment strength in our sample is strongest between red central galaxies and red satellites. On the contrary, the satellite distribution in systems with a blue central galaxy is perfectly consistent with isotropic. We also find that the alignment strength is stronger in more massive haloes and at smaller projected radii from the central galaxy. In addition, there is a weak indication that fainter (relative to the central galaxy) satellites are more strongly aligned.

Two conditions must be satisfied in order to produce the alignment observed here. First of all, the distribution of satellite galaxies in groups must be aspherical, and secondly, the orientation of central galaxies must be aligned with the distribution of satellite galaxies. Cosmological N-body simulations of CDM models have demonstrated clearly that CDM haloes are not spherical. The typical minor-to-major axis ratio is ~0.6, with a relatively large dispersion (e.g. Bullock 2002; Jing & Suto 2002). This is also supported by recent weak-lensing data (Hoekstra, Yee & Gladders 2004). As we argued in Section 1, simulations suggest that the angular distribution of dark matter subhaloes, which are expected to host satellite galaxies, is in reasonable agreement with that of the dark matter. Therefore, it seems reasonable to expect that the first condition is fulfilled. Explaining the anisotropy as reflecting the non-sphericity of the dark matter haloes is also consistent with our finding that the alignment strength increases with halo mass; after all, numerical simulations have shown that more massive haloes are less spherical (Warren et al. 1992; Bullock 2002; Jing & Suto 2002; Bailin & Steinmetz 2005; Kasun & Evrard 2005).

In order for the second condition to be fulfilled as well, the central galaxy must be somehow aligned with the principal axes of the mass distribution of its host halo. Here it is important to distinguish between disc galaxies, whose orientation is governed by their angular momentum vector, and spheroidal galaxies, whose orientation is somehow related to its formation history (typically thought to be merger driven).

In the standard picture of disc formation (e.g. Fall & Efstathiou 1980; Mo, Mao & White 1998), one assumes that baryons and dark matter have identical distributions of specific angular momentum (due to tidal torques from the cosmological density field), and that the baryons conserve their specific angular momentum when cooling to form a centrifugally supported disc. Since simulations have shown that the spin axis of dark matter haloes is well aligned with the minor axis of the halo, this simple picture predicts that the disc spin axis should be parallel to the minor axis of the halo, and thus that the distribution of satellites is aligned with the disc major axis. Somewhat surprisingly, disc galaxies (which are typically blue) are exactly the subsample that do not seem to reveal a significant alignment with their satellites.

Detailed hydrodynamical simulations, however, have shown that the spin axes of the baryons and the dark matter (in the absence of cooling) are only poorly aligned (van den Bosch et al. 2002; Chen et al. 2003; Sharma & Steinmetz 2005). In addition, if cooling is included in the simulations, the resulting discs are found to have spin axes that are very poorly aligned with the *original* (i.e. in the absence of baryons) minor axis of the halo (Bailin et al. 2005). This suggests that the (direction) of the angular momentum of the baryons is not well conserved during the disc formation process, and thus predicts that there is little if any alignment between the orientation of the disc and that of its satellite distribution. However, there may still be a clear alignment between the distribution of the satellites and the principal axes of the dark matter halo. This picture not only explains the lack of a significant alignment when stacking many disc galaxies, but also the pronounced alignment found for the MW system: it only requires that the major axis of the MW halo happens to be oriented along the spin axis of the MW disc. However, in a recent merger-driven disc formation theory of Robertson et al. (2006) that the disc galaxies can be produced through high angular momentum accretion of gas rich progenitors, the satellite galaxies will be preferentially aligned with the disc plane. Note also that the MW satellites galaxies have an average luminosity ratio that is significantly smaller than our central-satellite systems. Given this, for the MW case, as discussed in Kroupa et al. (2005), another plausible explanation of the MW (dwarf) satellite distribution is that, if most of the dwarves are not of dark matter dominated, but stem from one initial gas-rich parent satellite on an eccentric near polar orbit that interacted with the young MW, forming tidal arms semiperiodically as its orbit shrank, this signal shall be naturally expected.

Perhaps somewhat surprisingly, we find the strongest alignment between red central galaxies and red satellites. If the orientation of a red (early-type) central galaxy is a reflection of the orbital angular momentum of the progenitors that merged during its formation, one might naively expect that this orientation is also aligned with the major axis of the halo. After all, the orientation of the halo itself is largely governed by the directionality of its mass accretion (e.g. van Haarlem & van de Weygaert 1993; Tormen 1997). It is less clear, however, why the alignment should be so much stronger for red satellites than for blue satellites. In the standard picture of galaxy formation, once a satellite galaxy has been accreted by a bigger system, its gas reservoir is stripped, resulting in a fairly quick truncation of star formation; the galaxy will become red. In this simple picture, one thus expects the colour of a satellite galaxy to be a reflection of the time since it was accreted. If the orientation of a halo, and its population of galaxies, changes as function of time with respect to the large-scale matter distribution, one could envision that those satellites that were accreted at around the same time when the central galaxy formed, show a more pronounced alignment than those satellites that have only recently been accreted. As shown by Bailin & Steinmetz (2004), most haloes reveal some slow figure rotation, with an amplitude that can cause a directional change of more than 90° within a Hubble time. Figure rotation is thus a potential explanation for the satellite-colour dependence of the alignment strength.

Cosmological *N*-body simulations also show that more massive dark matter haloes in general have more elongated structures, and that the iso-density contours of the dark matter distributions are strongly aligned in the inner part of a halo (e.g. Jing et al. 1995; Jing & Suto 2002; Bailin & Steinmetz 2005). Thus, if the central galaxy in such a halo aligns with the inner part of the halo, and if the distribution of satellite galaxies traces the dark matter distribution, the major axis of the central galaxy is expected to align with the satellite distribution, and the alignment is expected to be stronger on smaller radii. This is in agreement with what we found in this paper.

In a recent study, Agustsson & Brainerd (2005a) used the GIF simulations (e.g. Kauffmann et al. 1999) to interpret the observed alignment signal between the host and satellite galaxies in the context of structure formation. They found that the alignment between the satellites and the host halo major axis is much stronger than that between the host and satellite galaxies in the observations. This would imply that the host galaxies are on some degree misaligned with the host haloes. Meanwhile a related interesting result was recently obtained by Mandelbaum et al. (2006a,b), who used the galaxy–galaxy weak-lensing signals in the SDSS observations to constrain the ellipticity of dark matter haloes. They found that, for spirals (lens), the ellipticity of halo and light is anti-aligned on a 1–2σ level, while for ellipticals (lens), the ellipticity of halo relative to light, $f_{\rm h} = e_{\rm halo}/e_{\rm light}$, increases with luminosity. Apparently, these findings are helpful to interpret the overall central-satellite galaxy alignment signals we obtained in this paper, especially the halo mass, luminosity and type dependences.

The discussion presented above shows that the results obtained in the present paper are in qualitative agreement with naive, theoretical expectations. In order to compare our results to theory in a more quantitative manner, one has to understand in more detail how central galaxies in different haloes form, how the formation processes affect the orientations of the central galaxies relative to the haloes, and how satellite galaxies trace the mass distribution within dark matter haloes. All these issues require detailed numerical simulations of galaxy formation in the cosmic density field. In addition, to study the colour dependence of the alignment, some basic treatment of star formation will be necessary. Semi-analytical techniques combined with high-resolution numerical simulations may be particularly suited for this purpose. We will return to these issues in a forthcoming paper (Kang et al. in preparation).

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